

Yb-free, SLM EDFA: comparison of 980-, 1470- and 1530-nm excitation for the core- and clad-pumping

M. Dubinskii^a, V. Ter-Mikirtychev^b, J. Zhang^a and I. Kudryashov^c,

^a U.S. Army Research Laboratory, AMSRD-ARL-SE-EO, 2800 Powder Mill Road, Adelphi, Maryland 20783

^b NovaWave Technologies, Inc., 900 Island Dr., Suite 101, Redwood City, CA 94065

^c Princeton Lightwave Inc., 2555 US Route 130, Cranbury, New Jersey, 08512

Abstract

We present the results of the experimental study and comparison of Yb-free, Er-doped, all-fiber, alignment free, single frequency (SF) fiber amplifiers operating under 980-, 1470- and 1530-nm pumping for the core- and clad-pumping architectures. In the single-mode core-pumped configuration Er-doped fiber amplifiers demonstrated 52% and 60% pump to output efficiencies for 980 and 1480 nm pump wavelength, respectively, producing over 140 mW of SF output power at seed wavelength ~1560 nm and over 180 mW at seed wavelength 1605 nm for 300 mW of pump power. At the same time, when clad pumped, Er-doped 20/125 DC LMA gain fiber demonstrates laser efficiencies of 22.4% pumped at 980 nm - up to 20 W of fiber-coupled diode laser pumping. The same LMA fiber demonstrates 33% optical-to-optical efficiency (46% slope efficiency versus absorbed power) when cladding-pumped with 1520-1530-nm fiber-coupled laser diode modules. Detailed analysis of these experiments is presented.

Keywords: Er-doped; diode-pumped; eye-safe; fiber lasers.

Introduction

Current developments in the eye-safe ~1.5-um Yb-Er-doped fiber lasers (where Er excitation is accomplished via Yb) are quite impressive. Output power of Er-Yb fiber lasers with diffraction limited beam quality reached ~300 W power level and continue to grow. However, multi-hundred Watt power Yb-Er fiber laser systems already contain in their output a significant fraction of Yb emission (either narrowband or ASE) in the 1- μ m spectral range, thus significantly compromising any eye-safe application of this type of fiber laser systems. This problem, as well as pretty limited power conversion efficiency of the Er-Yb laser systems (typically, 35-40%), motivated researchers to go back and re-analyze the potential of introduced in 80's (approach first demonstrated by E. Snitzer) direct excitation of Er fiber lasers in Yb-free fibers.

Our recent successes with resonantly pumped Er:YAG bulk solid-state lasers [1, 2] point to significant advantages of direct resonant pumping of Er compared to pumping Yb-Er co-doped laser materials. In the meantime, very little is done in evaluating direct pumping of Er³⁺ in Er-only doped (Yb-free) fiber lasers, especially as it relates to high

Report Documentation Page

*Form Approved
OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 2008	2. REPORT TYPE	3. DATES COVERED 00-00-2008 to 00-00-2008			
4. TITLE AND SUBTITLE Yb-free, SLM EDFA: comparison of 980-, 1470- and 1530-nm excitation for the core- and clad-pumping		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory, AMSRD-ARL-SE-EO, 2800 Powder Mill Road, Adelphi, MD, 20783		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT see report					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified	Same as Report (SAR)	10	

power applications (multi-Watts of output laser power and more), and very few results on scalable in nature cladding-pumped operation of Er-only doped fiber lasers were reported. Because of quite high power density required for bleaching the ground-state absorption loss in the three-level Er-doped systems, most efforts were focused on core pumping geometry using either high brightness 980-nm dye or diode lasers [3] or Raman shifted fiber lasers [4] operating in the 1480-nm spectral range. To the best of our knowledge, the only efforts aimed at “non-telecom power level” scaling of resonantly cladding-pumped Yb-free Er fiber lasers were reported in [6] and [7]. While in both these cases output power level of ~1W was achieved, neither of these efforts was targeting ultimate power scaling by also addressing generation (or amplification) of the single-frequency laser radiation most suitable for further power scaling, e.g., via beam combining. Of the two mentioned efforts only one ([7]) was actually targeting the most scalable LMA fiber case.

Here we present the detailed comparative study of the two fundamentally different Er fiber amplifier systems, core-pumped and cladding-pumped, under 980-, 1470-, and 1530-nm fiber coupled laser diode excitation, which corresponds to either higher energy manifold (~975-nm-pumping into $^4I_{11/2}$ manifold of Er^{3+} ion) excitation or direct $^4I_{15/2} \rightarrow ^4I_{13/2}$ Er^{3+} ion excitation into its lowest absorption band at 1470 nm and 1530 nm. In all experiments described below we used either commercially available (COTS, OFS) MP980, single mode, 50 m long, Er only doped fiber (core pumped case) or COTS (Liekki) Er60-20/125DC double clad, Er only doped LMA fiber. All experiments were carried out at room temperature and in a CW operational mode. Diffraction limited beam quality of the LMA gain fiber output was monitored by M2 measurements and numerical aperture of the output laser radiation.

1. Yb-free Er fiber amplifier: CORE pumping geometry

a) 980 nm pumping

An experimental set-up of core pumped Er only doped fiber laser MOPA system was based on a low power fiber coupled master oscillator (butterfly-package fiber coupled DFB diode laser) amplified in MP980 Er-doped fiber amplifier. All diode lasers including master oscillator (MO) and pump diodes were fiber coupled and spliced with the rest of system fiber components and were, therefore, alignment free. MO was separated from fiber amplifier by a single-stage fiber coupled optical isolator. MO used was a 1560 nm single longitudinal mode, fiber coupled, DFB diode laser with over 30 mW of CW output power. A 980/1560 WDM was used as a pump power coupler.

As seen from Fig. 1, the core-pumped fiber amplifier - when pumped at 980 nm - exhibits over 50% pump to laser conversion efficiency. The core-pumped fiber laser output spectral distribution was measured using Ando AQ6315E optical spectrum analyzer (Fig. 2). As seen from Fig. 2, the laser exhibits single longitudinal mode operation and over 30 dB signal to ASE contrast ratio. Because of the limited

spectrometer resolution we were unable to measure the actual laser bandwidth. We observed no nonlinearities which could challenge the fiber laser power scaling.

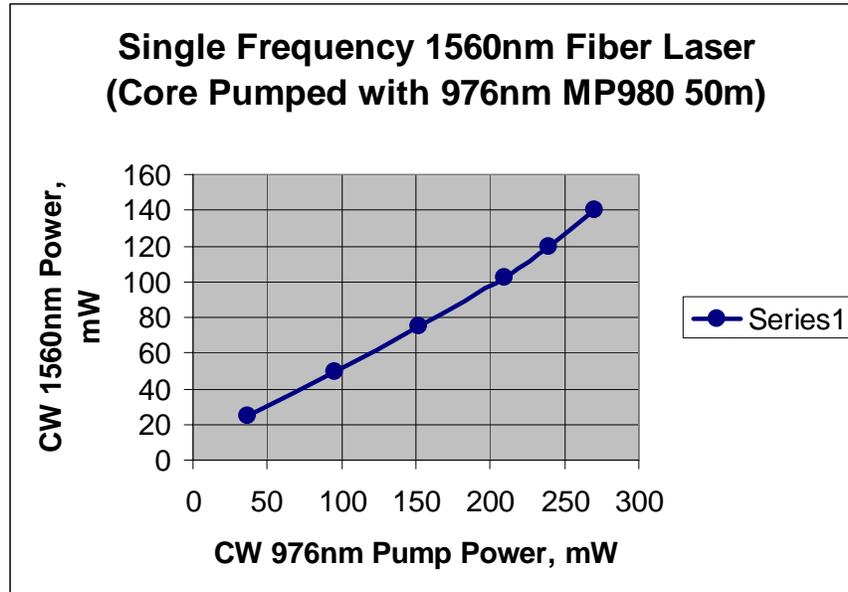


Figure 1. Output versus input for core-pumped at 980 nm MP980 fiber amplifier.

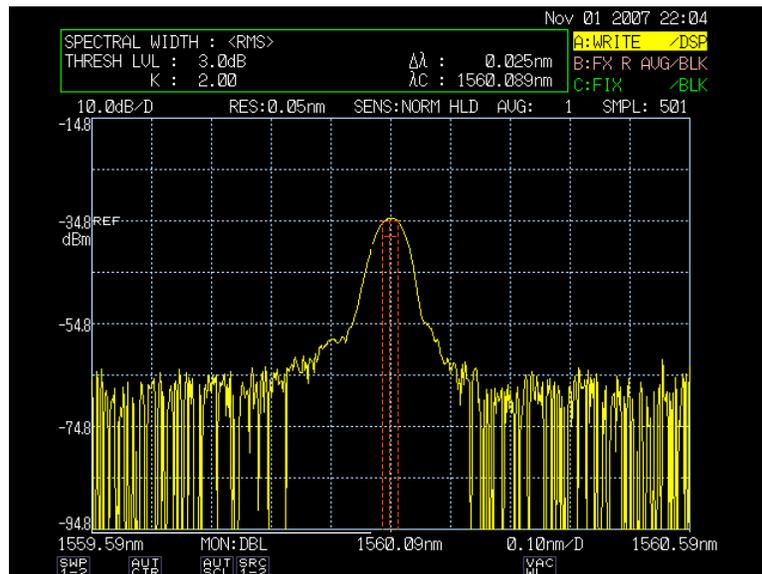


Figure 2. Fiber laser output spectral distribution measured by Ando AQ6315E optical spectrum analyzer

The laser demonstrates diffraction limited beam quality and shows no sign of output power saturation versus pump power and therefore is considered to be in a pump limited high efficiency regime.

b) 1480 nm pumping

Core pumped 1480nm fiber laser has been constructed using the same MP980 OFS COTS, 50 m long fiber amplifier. The only difference with the design for the case of 980 nm pump was that the different WDM (1480/1560) and different pump diode laser were used.

The output power versus pump power for 1480 nm pumping is shown in Fig. 3. For convenience of comparison, experimental results with 1480 nm pump source are shown overlaid with the results presented in Fig.1. As can be seen from Fig. 3, the 1480-nm core pumped fiber laser demonstrates over 60% power conversion efficiency. That is about 20% higher slope than was observed with the 980-nm pumping in the same amplifier configuration. It is necessary to note that the length of active fiber was not optimized. Much better results are expected after optimization.

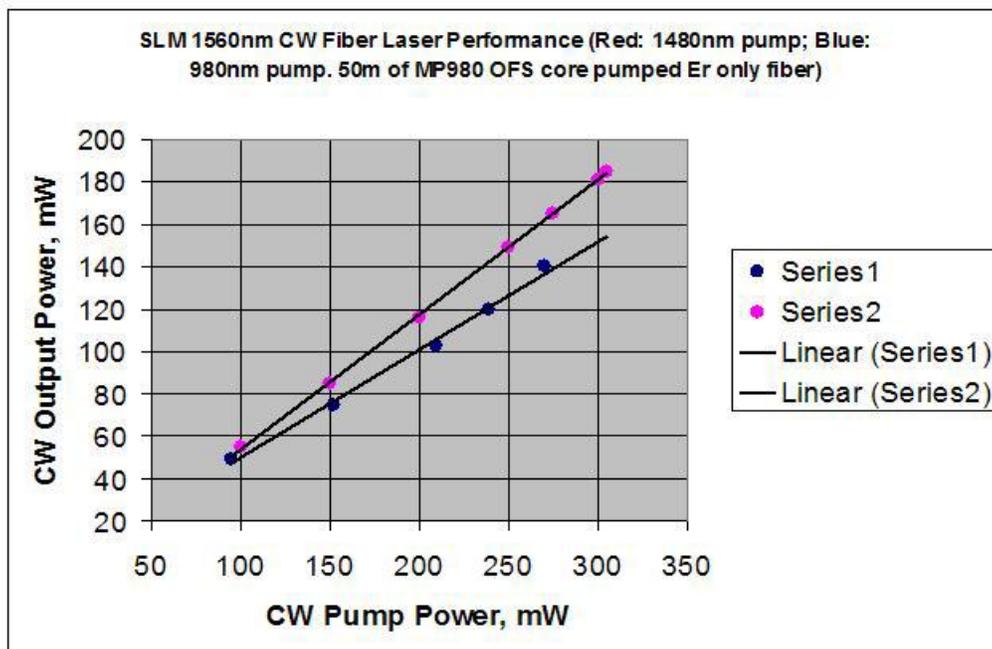


Figure 3. Output power versus pump power for the 1470 and 980 nm pump wavelength for core pumped Er-doped fiber amplifier.

2. Yb-free Er fiber amplifier: CLAD pumping geometry

a) 980nm pumping

Experimental setup used in our clad-pumped experiments is shown in Fig. 4. It includes the semiconductor single frequency DFB laser at 1560 nm, single-mode fiber pre-amplifier based on a standard (COTS) polarization maintaining PM EYDF-7/130 fiber (Nufern) and, finally, Er-only doped fiber booster amplifier based on a standard (COTS) Er60-20/125DC Liekki LMA fiber. Standard two 4W fiber-coupled laser diode pumps were used to pump pre-amplifier. Fiber-coupled optical isolators were used to isolate pre-amplifier and fiber laser-booster amplifier.

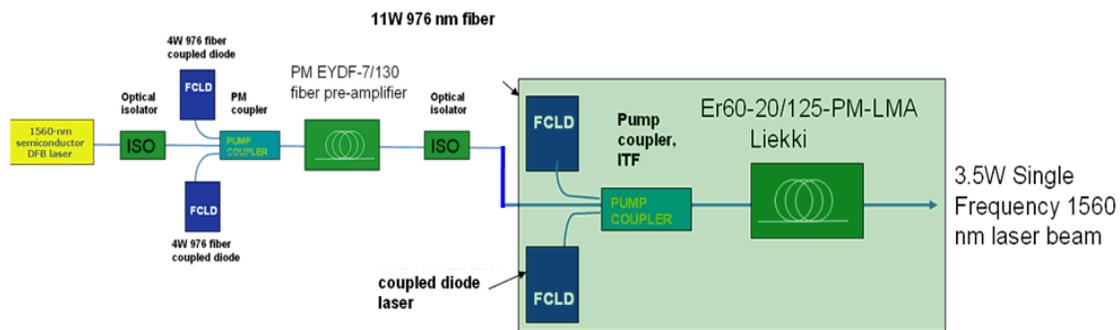


Figure 4. Optical layout of the 1560-nm Master Oscillator-Power Amplifier (MOPA) system used for testing of Er-only doped Er60-20/125 LMA fiber amplifier.

Booster amplifier was cladding-pumped (co-pumped only) by the two 11-W 976-nm fiber-coupled (105/125, NA 0.22) diode lasers (JDSU).

Experimental results (output power at 1560 nm versus pump power) for Er-only doped Er60-20/125DC booster amplifier are shown in Fig. 5. The slope efficiency of about 22% was achieved. As can be seen from Fig. 5, the booster amplifier works well beyond the saturation (pre-amplifier output launched into the booster after the optical insulator was measured at about 1W, while the power required for booster saturation was estimated to be ~130 mW, which is enough to produce 90% of the booster output power, even without careful system optimization.

This cladding pumped fiber laser demonstrated diffraction limited beam quality when the fiber was coiled to ~35 mm diameter, shows no sign of output power saturation versus pump power and therefore is considered a pump limited, high efficiency amplifier.

The laser exhibits single longitudinal mode operation. Good correspondence of the experimental energy parameters with that of theoretical modeling has also been observed (see Fig. 5).

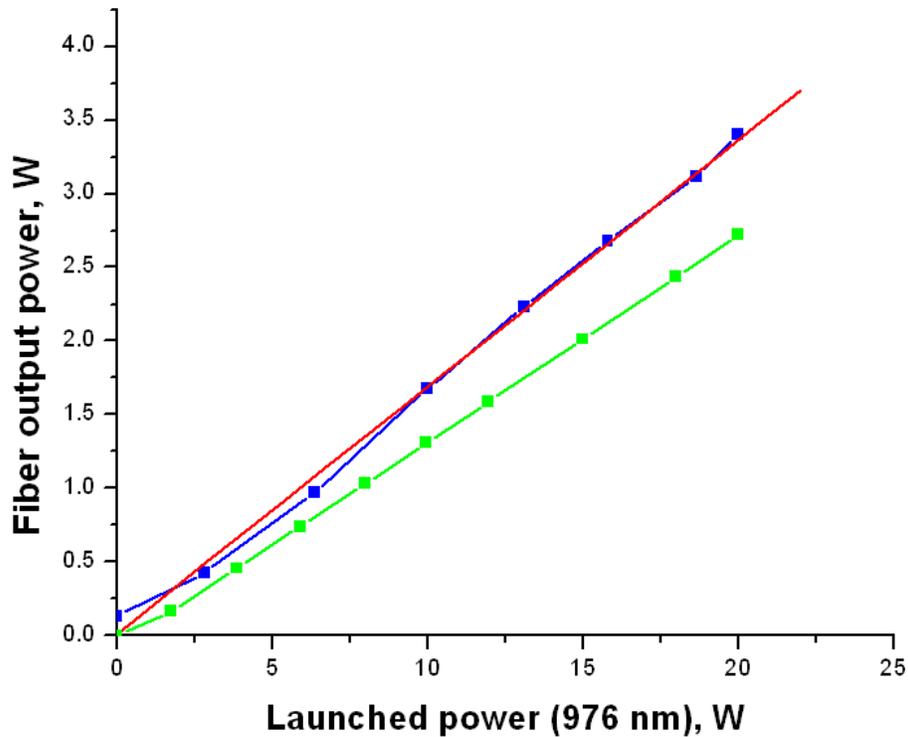


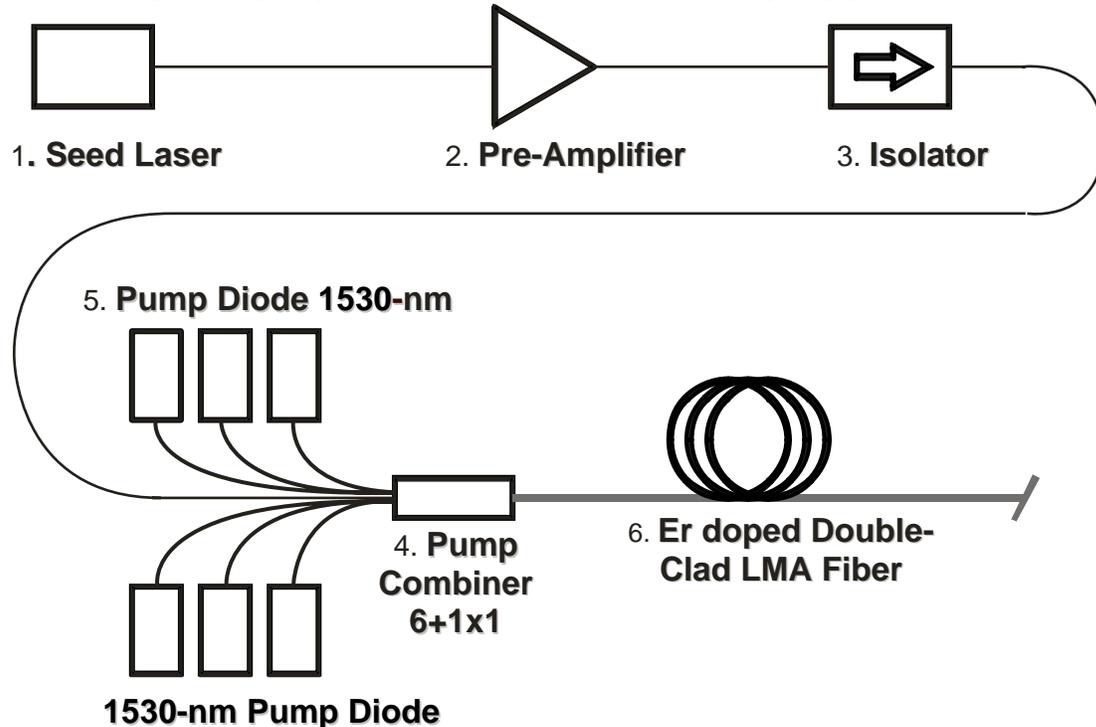
Figure. 5. Er-only doped Er60-20/125DC booster amplifier single-frequency/ Single-mode output power at 1560 nm versus pump power (976 nm) with the fixed incoming pre-amplifier power of 1 W. Green – simulation, blue - experiment

Presented laser characterization results of an all-fiber cladding-pumped Er-only doped Er60-20/125 LMA amplifier with 976 nm pumping are indicating diffraction-limited, single-frequency output of 3.5 W, which is believed to be the highest reported to-date power out of this type of amplifier.

b) 1530nm pumping

The cladding pumped fiber laser amplifier clad-pumped at 1530 nm with high power laser diode modules consists of tunable seed laser, C-band power pre-amplifier and Er60-20/125DC fiber based power booster (Fig. 6). Power level of pre-amplified seed laser was about 400 mW. The longest wavelength for this setup was 1570 nm. The maximum

power, as well as the longest wavelength, in this experiment were both limited by the available C-band amplifier. The co-pump configuration was utilized for the booster section. Pump power was delivered by the 6 laser diode pump modules via 6-port pump combiner. About 5-6 W, coupled into the 105/125 μm multimode fibers with 0.15 numerical aperture, pump radiation was launched into each pump port.



- 1530-nm Pump Diode**
- Single frequency Laser, 6dBm output
 - 0.5 W C-band EDFA
 - OFR 5W 1550nm optical isolator
 - 6+1x1 SIFAM MM pump combiner (loss ~11-12% at 1530 nm)
 - Six 1520-1530 nm 5-6 W pump diode lasers, 100 μm core 0.15NA pigtail
 - Liekki Er60-20/125DC, 9 meters

Figure 6. Experimental set-up of 1530 nm cladding pumped Er-doped LMA fiber amplifier.

The measured pump combiner loss for the power launched into its ports was about 11%. This allowed delivering up to 30W of CW pump power into the clad of the gain fiber (see Fig. 7). All pump diode modules were mounted on a common cold plate without active stabilization of their temperature. The individual pump diode lasers were not pre-selected for a very specific spectral position. As a result, the collective spectral width of pumping radiation was about 20 nm. Typical combined 6-module spectrum after the combiner is shown in Fig. 8.

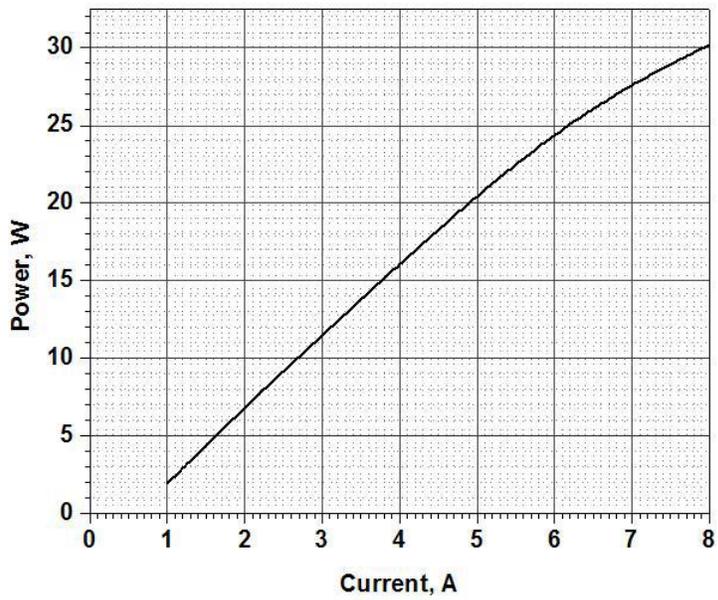


Figure 7. Total pump power at the pump combiner output versus laser diode pump current.

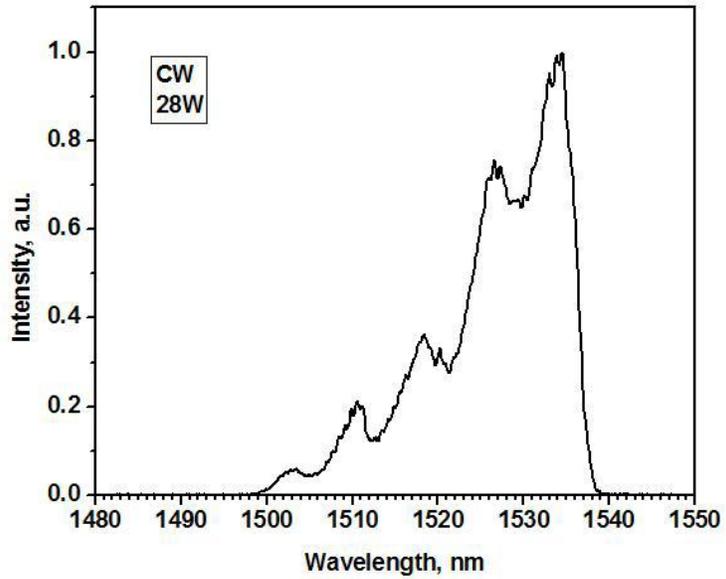


Figure 8. Typical spectrum of the six 1530nm diode lasers combined in clad pumping experiments.

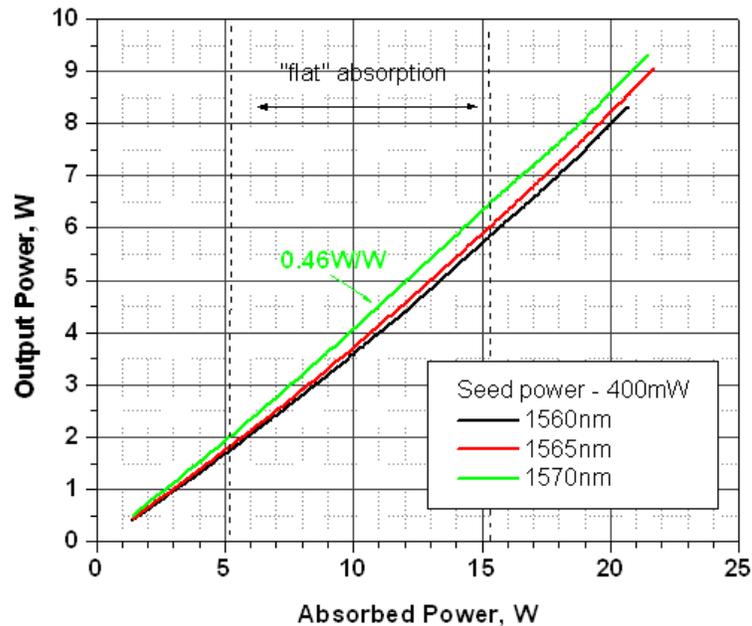


Figure 9. Performance of the cladding-pumped LMA fiber amplifier for the three different seed laser wavelength. Pump wavelength - 1530nm, wideband (20 nm).

The performance of the amplifier was tested at seed wavelengths 1560, 1565 and 1570 nm. Output power versus absorbed power dependences are demonstrated in Fig. 9. The conversion efficiency was measured in a range of pump powers where absorption coefficient does not depend on pump power. With the seed wavelength of 1570 nm the fiber amplifier demonstrates the highest conversion efficiency of 46% with respect to absorbed pump power (33% optical to optical efficiency). The maximum output power at this wavelength was over 9.3 W. We observed no output power saturation with increasing pump power. We could detect neither nonlinear effects nor ASE power, which limit the amplifier performance. Obtained diffraction-limited, single-frequency output of 9.3 W is believed to be the highest reported to-date power out of this type of amplifier.

Conclusions

We performed comparative experimental study of both the core and the cladding pumped Yb-free Er-doped fiber amplifiers for the non-resonant (980nm) and the resonant (1480-1530nm) pumping. In the case of core-pumped geometry without any optimization of the amplifier we demonstrated optical efficiency about 20% higher for the resonant 1470 nm pumping wavelength compared with the 980 nm pumping. For the case of cladding-pump geometry diffraction-limited, single-frequency, output of 3.5 W for 976 nm pumping and 9.3 W for 1530nm pumping were obtained, and are both believed to be the highest reported to-date powers out of these types of amplifiers based on Yb-free Er-doped fiber. For the resonant pumping, the Yb-free Er-doped high power amplifier with

pump wavelength of 1530 nm exhibits optical-to-optical conversion efficiency of ~ 33% (46% slope efficiency versus absorbed power).

Acknowledgment: Part of this work was supported by the High Energy Laser Joint Technology Office.

References

- [1] D. Garbuzov, I. Kudryashov and M.A. Dubinskii, "Resonantly diode laser pumped 1.6- μm -erbium-doped yttrium aluminum garnet solid-state laser", *Appl. Phys. Lett.* **86**, 131115 (2005)
- [2] D. Garbuzov, I. Kudryashov and M.A. Dubinskii, "110 W (0.9 J) pulsed power from resonantly diode-laser-pumped 1.6- μm Er:YAG laser" - *Appl. Phys. Lett.* **87**, 121101 (2005)
- [3] W.H.Loh, and J.P.de Sandro, "Suppression of self-pulsing behavior in erbium-doped fiber lasers with resonant pumping: experimental results", *Opt.Letts*, vol.21, 1996, pp1475-1477.
- [4] J.C.Jasapara, M.J.Andrejco, A.D.Yablon, J.W.Nicholson, C.Headley and D.DiGiovanni "Picosecond pulse amplification in a core-pumped large-mode-area erbium fiber", *Opt.Letts*, vol.32, 2007, pp.2429-2431.
- [5] P. Bousselet, M. Bettiati, L. Gasca, P. Lambelet, F. Leplingard, D. Bayart. "+30 dBm output power from a cladding-pumped Yb-free EDFA for L-band applications," - In *Optical Amplifiers and Their Applications Conference'2001*, Conference Digest, Pap. OWC-3.
- [6] D.Walton, L.Zenteno, A.Ellison, J.Anderson, X.Liu, L.Hughes, C.Caneau and C.Zah "Resonantly pumped double clad erbium-doped fiber laser" *CLEO'2003 Conference Proceedings*, OSA, CMK-5.
- [7] J.D.Minelly, V. Stasyuk, J.P. de Sandro, E. Gagnon, S. Chatigny, "Yb-free high energy double-clad Er fiber amplifier" - *Optical Amplifiers and their Applications (OAA 2004)*, June 27-30 2004, San Francisco, CA, Postdeadline paper: PD4-1.